

ON THE STATISTICAL CHARACTERIZATION OF FLOWS IN INTERNET TRAFFIC WITH APPLICATION TO SAMPLING

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ABSTRACT. A new method of estimating some statistical characteristics of TCP flows in the Internet is developed in this paper. For this purpose, a new set of random variables (referred to as observables) is defined. When dealing with sampled traffic, these observables can easily be computed from sampled data. By adopting a convenient mouse/elephant dichotomy also *dependent on traffic*, it is shown how these variables give a reliable statistical representation of the number of packets transmitted by large flows during successive time intervals with an appropriate duration. A mathematical framework is developed to estimate the accuracy of the method. As an application, it is shown how one can estimate the number of large TCP flows when only sampled traffic is available. The algorithm proposed is tested against experimental data collected from different types of IP networks.

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1. INTRODUCTION

In Internet traffic a flow is classically defined as the set of those packets with the same source and destination IP addresses together with the same source and destination port numbers and the same protocol type. It is well known that if large TCP flows carry the prevalent part of traffic (in Bytes), most of flows are small (in number of packets). A formal definition of “large” and “small” will be given later in the paper. As it will be seen, it may depend on the context; in a first step, the discussion is kept informal.

We investigate in this paper how to characterize the statistical properties of the sizes of large flows (notably their number of packets) in Internet traffic. It is commonly observed in the technical literature and in real experiments that the

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total size (in packets or bytes) of such flows has a heavy tailed distribution. In practice, however, this characterization holds only for very large values of the flow size. Consequently, in order to accurately estimate the tail of the size probability distribution, a large number of large flows is necessary. To increase the sample size when empirically estimating probability distribution tails, one is led to increase the length of the observation period. But the counterpart is that the distribution of the flow size can no more be described in terms of simple probability distributions, of the Pareto type for example. This is due to the fact that traffic is not stationary over long time periods, for instance because of daily variations of interactive services (video, web, etc.).

Actually, numerous approaches have been proposed in the technical literature in order to model large flows as well as their superposition properties. One can roughly classify them in two categories: signal processing models and statistical models. Using ideas from signal processing, Abry and Veitch [1], see also Feldman *et al.* [14, 15] and Crovella and Bestavros [8], describe the spectral properties of the time series associated with IP traffic by using wavelets. In this way, a characterization of long range dependence (the Hurst parameter for example) can be provided. Straight lines in the log-log plot of the power spectrum support some of the “fractal” properties of the IP traffic, even if they may simply be due to packet bursts in data flows. See Rolland *et al.* [23].

Signal processing tools provide information on aggregated traffic but not on characteristics on individual TCP flows, like the number of packets or their transmission time. For statistical models, a representation with Poisson shot noise processes (and therefore some independence properties) has been used to describe the dynamics of IP traffic, see Hohn and Veitch [17], Duffield *et al.* [11], Gong *et al.* [16], Barakat *et al.* [4] and Krunz and Makowski [18] for example. In Ben Azzouna *et al.* [3], Loiseau *et al.* [20, 19] and Gong *et al.* [16], the distribution of the size of large flows is represented by a Pareto distribution, i.e. a probability distribution whose tail decays on a polynomial scale.

The starting point of some of these analyses is the need for understanding the relation between the distribution of the number \hat{S} of sampled packets when performing packet sampling and the distribution of the flow size S . The problem can be described as follows: $\mathbb{P}(\hat{S} = j) = Q(\mathbb{P}(S = \cdot), j)$, $j \geq 1$, with

$$Q(\phi, j) = p^j \sum_{\ell=j}^{+\infty} \binom{\ell}{j} (1-p)^{\ell-j} \phi(\ell).$$

The problem then consists of finding a distribution ϕ_0 maximizing some functional $\mathcal{L}(\phi)$ so that the relation $\mathbb{P}(\hat{S} = j) = Q(\phi, j)$ holds. See Loiseau *et al.* [19] for an extensive discussion of the current literature where our algorithm is called “stochastic counting”. As it will be seen in the following, we will not rely on the maximum likelihood ratio of distributions in our approach but on estimations of some averages to estimate some key parameters.

Statistical Characterization Method. We develop in this paper an alternative method of obtaining a statistical description of the size of large flows in IP traffic by means of a Pareto distribution: Statistics are collected during successive time windows of limited length (instead of one single time window for the whole trace). It must be emphasized that this characterization in terms of a Pareto distribution does

not rely on the asymptotic behavior of the tail distribution but only on statistics on some range of values for the sizes of flows.

The advantage of the proposed method is that with a careful procedure, a simple statistical characterization is possible and seems to be quite reliable as shown by our experiments for various sets of traffic traces. The intuitive reason for considering short time periods is that on such times scales, flows exhibit only one major statistical mode (typically a Pareto behavior). In larger time windows, different modes due to the wide variety of flows and non-stationarity in IP traffic necessarily appear. (See Feldman *et al.* [15].) This approach allows us to establish a reliable statistical characterization of flows which is used to infer information from sampled traffic as it will be seen. The counterpart of that the distribution of the *total* size of a large flow (obtained when considering the complete traffic trace) cannot be obtained directly in this way since the trace is cut into small pieces.

An algorithm is proposed to obtain the statistical representation of large flows when all the packets of the trace are available. The constants used in our algorithms are explicitly expressed as either universal constants (independent of traffic) or constants depending on traffic : Length of the observation window, definition of TCP flows referred to as large flows, etc. The procedure invoked to estimate flow statistics should not depend on some hidden pre-processing of the trace. Our algorithms determine *on-line* the constants depending on the traffic. This is, in our view, one important aspect which is sometimes neglected in the technical literature

Application to Sampled Traffic. The basic motivation for developing a flow characterization method is to infer flow characteristics from sampled data. This is notably the case for sampling processes such as the 1-out-of- k sampling scheme implemented by CISCO's NetFlow [7], which greatly degrades information on flows. What we advocate in this paper is that it is still possible to infer relevant characteristics on flows from sampled data if some characteristics of the flow size can be confidently described by means of a simple Pareto distribution. By using the statistical representation described above, we propose a method of inferring the number of large flows from sampled traffic.

The proposed method relies on a new set of random variables, referred to as observables and computed in successive time intervals with fixed length. Specifically, these random variables count the number of flows sampled once, twice or more in the successive observation windows. The properties of these variables can be obtained through simple characteristics, in particular *mean values* of variables instead of *remote quantiles* of the tail distribution, which are much more difficult to accurately estimate. By developing a convenient mathematical setting (Poisson approximation methods), it is moreover possible to show that quantities related to the observables under consideration are close to Poisson random variables with an explicit bound on the error. This Poisson approximation is the key result to estimate the total number of large flows.

Organization of the paper. The organization of the paper is as follows. A statistical description of large TCP flows is presented in Section 2, this representation is tested against five exhaustive sets of traffic traces: three from the France Telecom (FT) commercial IP network carrying residential ADSL traffic and two others from Abilene network. An algorithm is developed in this section to compute the characteristics of the Pareto distributions describing flows. In Section 3, some assumptions

on sampled traffic are introduced and the observables for describing traffic are defined. The mathematical properties are analyzed in light of Poisson approximation methods in Section 4. The results developed in this section are crucial to infer the statistics of an IP traffic from sampled data. Experiments with the five sets of sampled traces used in this paper are presented and discussed in Section 5. Some concluding remarks are presented in Section 6.

2. STATISTICAL PROPERTIES OF FLOWS

This section is devoted to a statistical study of the size (the number of packets) of flows in a limited time window of duration Δ . The goal of this section is show that a simple statistical representation of the flow size can be obtained for various sets of traffic traces.

2.1. Assumptions and Experimental Conditions.

The sets of traces used for testing theoretical results. For the experiments carried out in the following sections, several sets of traces will be considered: Commercial IP traffic, namely ADSL traces from the France Telecom (FT) IP collect network, and traffic issued from campus networks (Abilene III traces). Their characteristics are given in Table 1.

TABLE 1. Characteristics of traffic traces considered in experiments.

Name	Nb. IP packets	Nb. TCP Flows	Duration
ADSL Trace A	271 455 718	20 949 331	2 hours
ADSL Trace B Upstream	54 396 226	2 648 193	2 hours
ADSL Trace B Downstream	53 391 874	2 107 379	2 hours
Abilene III Trace A	62 875 146	1 654 410	8 minutes
Abilene III Trace B	47 706 252	1 826 380	8 minutes

The Abilene traces 20040601-193121-1.gz (trace A) and 20040601-194000-0.gz (trace B) can be found at the url <http://pma.nlanr.net/Traces/Traces/long/ipls/3/>.

Time Windows. Traffic will be observed in successive time windows with length Δ . In practice, the quantity Δ can vary from a few seconds to several minutes depending upon traffic characteristics on the link considered.

The ideal value of Δ actually depends on the targeted application. For the design of network elements considering the flow level (e.g., flow aware routers, measurement devices, etc.), it is necessary to estimate the requirements in terms of memory to store the different flow descriptors. In this context, Δ may be of the order of few seconds. The same order of magnitude is also adapted to anomaly detection, for instance for detecting a sudden increase in the number of flows. For the computation of traffic matrices, Δ can be several minutes long (typically 15 minutes). In our study, the “adequate” values for Δ are of the order of several seconds. See the discussion below.

Mice and Elephants. With regard to the analysis of the composition of traffic, in light of earlier studies on IP traffic (see Estan and Varghese [13], Papagiannaki *et al.* [22] or Ben Azzouna *et al.* [2]), two types of flows are identified: small flows with few packets (referred to as mice) and the other flows will be referred to as elephants. In commercial IP traffic, this simple traffic decomposition can be justified by the predominance of web browsing and peer-to-peer traffic giving rise to either signaling and very small file transfers (mice) or else file downloads (elephants).

This dichotomy may be more delicate to verify in a different context than the one considered in Ben Azzouna *et al.* [2]. For LAN traffic, for example, there may be very large amounts of data transferred at very high speed. As it will be seen in the various IP traces used in our analysis, the distinction between mice and elephants has to be handled with care and in our case is dependent on the type of traffic considered. The distinction between the constants depending on the trace and “universal” constants is, in our view, a crucial issue. It amounts to precisely stating which constants are *depend* on traffic. This aspect is generally (unduly in our opinion) neglected in traffic measurement studies. In particular, the variable Δ and the dichotomy mice/elephants are dependent on the trace, as explained in the next section.

2.2. Heavy Tails. The fact that the distribution of the size S of a large TCP flow is heavy tailed is well known. Experiments and theoretical results on the superposition of ON-OFF heavy tailed traffic have justified the self similar nature of IP traffic, see Crovella and Bestavros [8]. Although the heavy tailed property of the size of large flows is commonly admitted, little attention has been paid to identify properly a class of heavy tailed distributions so that the corresponding parameters can be estimated for an arbitrary traffic trace with a significant duration.

One of the reasons for this situation is that the most common heavy tailed distributions $G(x) = \mathbb{P}(S \geq x)$ (e.g., Pareto, i.e., $G(x) = C/x^\alpha$ for $x \geq b$ and some $\alpha > 0$, or Weibull, i.e., $G(x) = \exp(-\nu x^\beta)$ for some $\beta > 0$ and $\nu > 0$) have a very small number of parameters and consequently a limited number of possible degrees of freedom for describing the distribution of the sizes of flows. For this reason, such a distribution can rarely represent the statistics of the total number of packets transmitted by a flow in a trace of arbitrary duration.

As a matter of fact, if a traffic trace is sufficiently long, some non stationary phenomena may arise and the diversity of file sizes may not be captured by one or two parameters. For example, with a Pareto distribution, the function $x \rightarrow G(x)$ in a log-log scale should be a straight line. The statistics of the file sizes in the traces used in our experiments are depicted in Figure 1 and 2 for an ADSL traffic trace from the France Telecom backbone IP collect network and for a traffic trace from Abilene network, respectively.

Figure 1 and 2 clearly show that for the two traffic traces considered, the file size exhibits a multimodal behavior: At least *several* straight lines should be necessary to properly describe these distributions. These figures also exhibit the (intuitive) fact that has been noticed in earlier experiments: The longer the trace is, the more marked is the multimodal phenomenon. (See Ben Azzouna *et al.* [3] for a discussion.)

The *key observation* when characterizing a traffic trace is the fact that if the duration Δ of the successive time intervals used for computing traffic parameters is appropriately chosen, then the distribution of the size of the main contributing flows

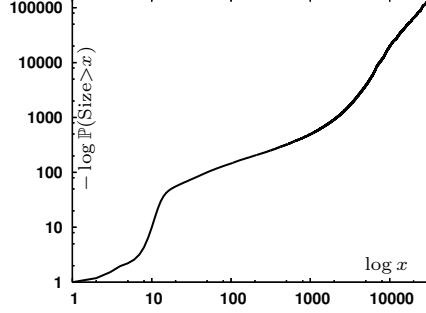


FIGURE 1. Statistics of the number of packets S of a flow for ADSL A (2 hours): the quantity $-\log(\mathbb{P}(S > x))$ as a function of $\log(x)$.

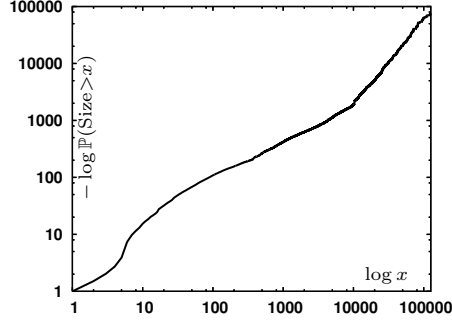


FIGURE 2. Statistics of the number of packets S of a flow for ABILENE A trace (8 minutes): the quantity $-\log(\mathbb{P}(S > x))$ as a function of $\log(x)$.

in the time interval can be represented by a Pareto distribution. More precisely, there exist Δ , B_{min} , B_{max} and $a > 0$ such that if S is the number of packets transmitted by a flow in Δ time units, then $\mathbb{P}(S \geq x \mid S \geq B_{min}) \sim P_\alpha(x)$ for $B_{min} \leq x \leq B_{max}$ with

$$(1) \quad P_\alpha(x) \stackrel{\text{def.}}{=} \left(\frac{B_{min}}{x} \right)^a, \text{ for } x \geq B_{min},$$

and furthermore the proportion of large flows with size greater than B_{max} is less than 5%. The parameter B_{min} is usually referred to as the location parameter and a as the shape parameter.

In other words, if the time interval is sufficiently small then the distribution of the number of packets transmitted by a large flow has one dominant Pareto mode and therefore can confidently be characterized by a unique Pareto distribution. The algorithm used to validate this result is described in Table 2. It is run from the beginning of the trace; in practice a couple of minutes is sufficient to obtain results for the constants Δ , B_{min} , B_{max} . The algorithm is of course valid when the total trace is available for at least an interval of several minutes. In the case of sampled

traffic for which this algorithm cannot be used, another method will be proposed in Section 3.

TABLE 2. Algorithm for Identifying Δ and the Pareto Distribution.

—	Δ is fixed so that at least 1000 flows have more than 20 packets.
—	B_{max} is defined as the smallest integer such that less than 5% of the flows have a size greater than B_{max} .
—	A Least Square Method, see Deuffhard and Hohmann [9] for example, is performed to get a linear interpolation in a log-log scale of the distribution of sizes between B_{min} and B_{max} . The constant B_{min} is chosen as the smallest integer such that the L_2 -distance in the sense of least square method with the approximating straight line is less than $2 \cdot 10^{-3}$. The slope of the line gives the value of the parameter a .

The quantity B_{min} defines the boundary between mice and *elephants* in the trace. A *mouse* is a flow with a number of packets less than B_{min} . An elephant is a flow such that its number of packets during a time interval of length Δ is greater than or equal to B_{min} . By definition of B_{max} , flows whose size is greater than B_{max} represent a small fraction of the elephants.

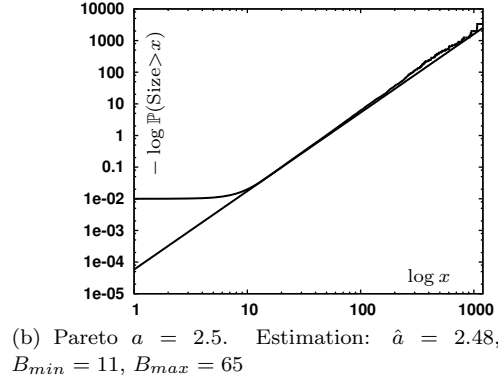
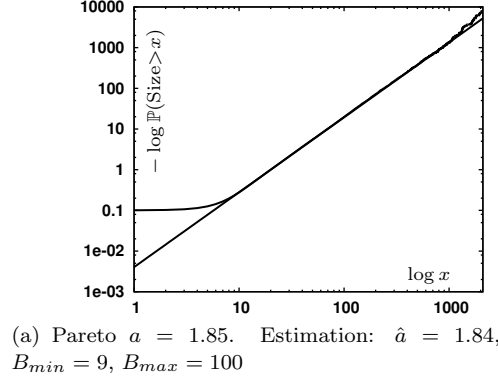
2.3. Experiments with Synthetic and Real Traffic Traces. Some experiments have been done using artificial traces with a real Pareto distribution. For these traces, the algorithm described in Table 2 has been used without any modification: A time window is defined when at least 1000 flows of size greater than 20 packets are detected. As it can be seen, the identification of the exponent a is quite good. Note that, because only Pareto distributed flows are present the minimal size B_{min} of elephants is smaller than in real traffic.

Experimental results with real traces, for the ADSL A and Abilene A traffic traces, are displayed in Figures 4 and 5, respectively. The same algorithm has been run for the ADSL trace B Upstream and Downstream as well as for the Abilene III B trace. The benefit of the algorithm is that the distribution of the number of packets in elephants can always be represented by a unimodal Pareto distribution if the duration of Δ is adequately chosen by using the algorithm given in Table 2. Results are summarized in Table 3.

TABLE 3. Statistics of the elephants for the different traffic traces.

	ADSL A	ADSL B Up	ADSL B Down	Abilene A	Abilene B
Δ (sec)	5	15	15	2	2
B_{min}	20	29	39	89	79
B_{max}	94	154	128	324	312
a	1.85	1.97	1.50	1.30	1.28

2.4. On the choice of parameters. We discuss in this section the various parameters used by the algorithm.

FIGURE 3. Synthetic traces with 10^6 flows with a Pareto distribution

Fixed parameters and parameters depending on traffic. There are four basic parameters for the model which are determined by the trace: Δ (duration of time window for statistics), the range of values $[B_{min}, B_{max}]$ for the Pareto distribution and the exponent a of this distribution. These parameters are discussed below.

Additionally there are “universal” (i.e. independent of the trace): the minimal number of flows to make statistics, set to 1000 here, the proportion, 5%, of flows of size $\geq B_{max}$, and the level of accuracy, $2 \cdot 10^{-3}$ here, of the least square method to determine B_{min} and B_{max} .

Parameter B_{min} . It turns out that for commercial (ADSL) traffic, the value of B_{min} is close to 20. This value is fairly common in earlier studies for classifying ADSL traffic. It should be noted that this value is not at all universal since, in our view, it does depend on traffic. The examples with Abilene traces, see below, which contain significantly bigger elephants, shows that the corresponding values should be higher than 20 (around 80 in our example).

The two types of traffic are intrinsically different: ADSL traffic is mainly composed of peer to peer traffic (with a huge number of small flows and a few file transfers of limited size because of the segmentation of large files into chunks),

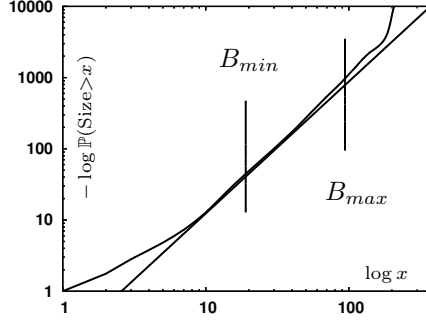
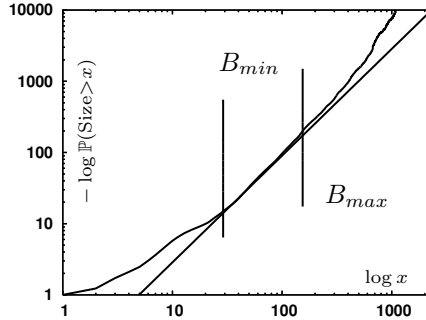
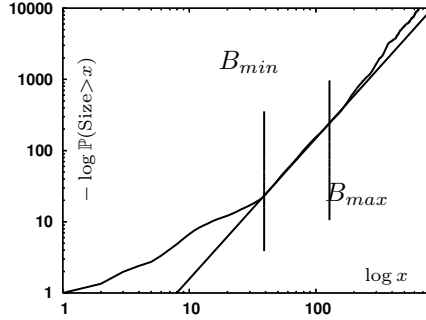
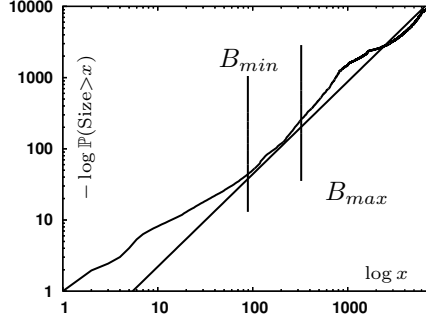
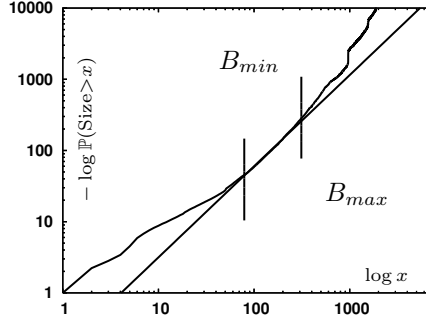

 (a) ADSL A trace – $\Delta = 5s$

 (b) ADSL B Down trace – $\Delta = 15$ seconds

 (c) ADSL B Up trace – $\Delta = 15$ s

 FIGURE 4. Statistics of the flow size (number of packets) in a time interval of length $\Delta = 15$

while Abilene traffic comprises large file transfers issued from campus networks. In order to maximize the range for the Pareto description, the variable B_{min} is defined as the smallest value for which the linear representation (in the log scale) holds.

Parameter Δ . This parameter Δ is determined in a simple way by our algorithm. According to the various experiments, the parameter Δ can be taken in some range of values where the Pareto representation still holds. On the one hand, Δ has to be taken large enough so that sufficiently many packets arrive in time intervals of duration Δ to derive reliable estimations of the Pareto distribution. An experiment

(a) Abilene A trace - $\Delta = 2$ s(b) Abilene B trace - $\Delta = 2$ sFIGURE 5. Statistics of the flow size (number of packets) in a time interval of length Δ for the Abilene traces.

with ADSL A trace with $\Delta = 1$ s gives only 63 flows of size more than 20 which is not enough to obtain reliable statistics. A “correct” value in this case is 5s. Experiments show that higher values (like 10s) do not change significantly the Pareto property observed in this case.

On the other hand, Δ should not be too large so that the statistical properties (a Pareto distribution in our case) can be identified, i.e., so that the statistics are unimodal. See Figures 1 and 2 which illustrate situations where statistics are done on the complete trace, i.e. when Δ is taken equal to the total duration of the trace. In these examples, the piecewise linear aspect of the curves suggests, for both cases, there is at least a bi-modal Pareto behavior.

2.5. Discussion. As it will be seen in the following, the above statistical model gives interesting results to extract information from sampled traffic. It has nevertheless some shortcomings which are now discussed.

A partial information when Δ is small. . It should be noted that the parameters computed in a time window of length Δ do not give a complete description of the distribution of the size of a large flow, since statistics are done over a limited time horizon. The procedure provides therefore a fragmented information.

To obtain a complete description of the statistics of the size of flows, it would be necessary to relate the statistics from successive time windows of length Δ . We

do not know how to do that yet. Nevertheless, as it will be seen in the following, this fragmented information can be recovered from sampled traffic and it will be used to give a good estimation on the number of active large flows at a given time. This incomplete but useful description of the statistics is, in some sense, the price to pay to have a simple estimation of the statistics of flows.

An incomplete description of large flows in a time window of size Δ . The representation with a Pareto distribution is for elephants (with size greater than B_{min}) whose size is less than B_{max} . In particular, it does not give any information on the statistics of flows with size greater than B_{max} . But note that, by definition, less than 5% of the total number of flows have a size greater than B_{max} . This is however a source of errors when, as in Section 4, the Pareto representation is used on the interval $[B_{min}, +\infty]$ instead of $[B_{min}, B_{max}]$

3. SAMPLED TRAFFIC: ASSUMPTIONS AND DEFINITION OF OBSERVABLES

In the previous section, an algorithm to describe the distribution of large flows by means of a unimodal distribution has been introduced. Now, it is shown how to exploit this algorithm in the context of packet sampling in the Internet. Packet sampling is a crucial issue when performing traffic measurements in high speed backbone networks. As a matter of fact, a fundamental problem related to the computation of flow statistics from traffic crossing very high speed transmission links is that, due to the enormous number of packets handled by routers, only a reduced amount of information can be available to the network operator.

Packet sampling is in this context an efficient method of reducing the volume of data to analyze when performing measurements in the Internet. One popular technique consists of picking up one packet every other κ_s packets with $\kappa_s = 100, 500, 1000$ in practice. (This sampling scheme is referred to as 1-out-of- κ_s packet sampling in the technical literature.) This method is implemented for instance in CISCO routers, namely NetFlow facility [7] widely deployed in operational networks today. It suffers from different shortcomings well identified in the technical literature, see for instance Estan *et al.* [12].

We describe in this section the different assumptions made on traffic in order to develop an analytical evaluation of our method of inferring flow statistics. Throughout this paper, high speed transmission links (at least 1 Gbit/s) will be considered.

3.1. Mixing condition. When observing traffic, packets are assumed to be sufficiently interleaved so that those packets of a same flow are not back-to-back but mixed with packets of other flows. This introduces some randomness in the selection of packets when performing sampling. In particular, when K flows are active in a given time window and if the i th flow comprises v_i packets during that period, then the probability of selecting a packet of the i th flow is assumed to be equal $v_i/(v_1 + v_2 + \dots + v_K)$. This property will be referred to as *mixing condition* in the following and is formally defined as follows. A variant of this property is, implicitly at least, assumed in the existing literature. See, e.g. Duffield *et al.* [10] and Chabchoub *et al.* [6].

Definition 1 (Mixing Condition). *If K TCP flows are active during a time interval of duration Δ , traffic is said to be mixing if for all i , $1 \leq i \leq K$, the total number \hat{v}_i of packets sampled from the i th flow during that time interval has the*

same distribution as the analog variable in the following scenario: at each sampling instant a packet of the i th flow is chosen with probability v_i/V where v_i is the number of packets of the i th flow and $V = v_1 + \dots + v_K$.

This amounts to claim that with regard to sampling, the probability of selecting a packet of a given flow is proportional to the total number of packets of this flow.

One alternative would consist of assuming that the probability of selecting a packet of the i th flow is $1/K$, the inverse of the total number of flows. This assumption, however, does not take into account the respective contributions of the different flows to the total volume and thus may be inaccurate. If all K flows had the same distribution with a small variance, then this assumption would not much differ from the mixing condition. Note however that the variance of Pareto distributions can be infinite if the shape parameter a is less than 2. Hence, this leads us to suppose that the mixing condition holds and that the probability of selecting a packet from flow i is indeed v_i/V .

3.2. Negligibility assumption. We consider traffic on very high speed links and it then seems reasonable to assume that no flows contribute a significant proportion of global traffic. In other words, we suppose that the contribution of a given flow to global traffic is negligible. In the following, we go one step further by assuming that in any time window, the number of packets of a given flow is negligible when compared to the total number of packets in the observation window. By using the notation of the previous section, this amounts to assuming that for any flow i , the number of packet v_i is much less than V . Furthermore, we even impose that the squared value of v_i is much less than V . We specifically formulate the above assumptions as follows.

Definition 2 (Negligibility condition). *In any window of length Δ , the square of the number of packets of every flow is negligible when compared to the total number of packets V in the observation window. There specifically exists some $0 < \varepsilon \ll 1$ such that for all $i = 1, \dots, K$, $v_i^2/V \leq \varepsilon$.*

The above assumption implies that no flows are dominating when observing traffic on a high speed transmission link. Table 4 shows that this is the case for the traces used in our experiments. There is thus no bias in the sampling process, which may be caused by the fact that some flows are oversampled because they contribute a significant part of traffic. This assumption is reasonable for commercial ADSL traffic because access links are often the bottlenecks in the network. For instance, ADSL users may have access rates of a few Mbit/s, which are negligible when compared against backbone links of 1 to 10 Gbit/s. Moreover, the bit rate achievable by an individual flow rarely exceeds a few hundreds of Kbit/s. In the case of transit networks carrying campus traffic, the above assumption may be more questionable since bulk data transfers may take place in Ethernet local area networks and individual flows may achieve bit rates of several Mbit/s.

3.3. The Observables. We now introduce the different variables used to infer flow characteristics. These variables are based only upon sampled data; they can be evaluated when analyzing NetFlow records sent by routers of an IP network. For this reason, these variables are referred to as observables. Because of packet sampling, recall that the original characteristics of flows (for instance their duration or their original number of packets) cannot be directly observed.

TABLE 4. The quantity $\mathbb{E}(v_1^2)/\mathbb{E}(V)$ for traffic traces considered in experiments.

Trace	$\Delta = 5\text{sec}$	$\Delta = 10\text{sec}$	$\Delta = 15\text{sec}$
ADSL A	0.000146	0.000159	0.000168
ADSL B up	0.001100	—	0.001335
ADSL B Down	0.002199	0.002543	0.002732

Trace	$\Delta = 1\text{sec}$	$\Delta = 2\text{sec}$	$\Delta = 3\text{sec}$	$\Delta = 5\text{sec}$
Abilene A	0.055001	0.068833	0.064813	0.072768

Trace	$\Delta = 1\text{sec}$	$\Delta = 2\text{sec}$
Abilene B	0.011786	0.013804

The observables considered in this paper to infer flow characteristics are the random variables W_j , $j \geq 1$, where W_j is the number of flows sampled j times during a time interval of duration Δ . The averages of the random variables W_j are in fact the key quantities used to infer the characteristics of flows from sampled data.

The random variables W_j , $j \geq 1$ are formally defined as follows: Consider a time interval of length Δ and let K be the total number of large flows present in this time interval. Each flow $i \in \{1, \dots, K\}$ is composed of v_i packets in this time interval. Let denote by \hat{v}_i the number of times that flow i is sampled. The random variable W_j is simply defined by

$$(2) \quad W_j = \mathbb{1}_{\{\hat{v}_1=j\}} + \mathbb{1}_{\{\hat{v}_2=j\}} + \dots + \mathbb{1}_{\{\hat{v}_K=j\}}.$$

In practice, if Δ is not too large, the data structures used to compute the variables W_j are reasonably simple. Moreover, as it will be seen in the following, provided that Δ is appropriately chosen, the statistics of the number of packets transmitted by elephants during successive time windows with duration Δ are quite robust. Consequently, the variables W_j inherit also this property. When the number of large flows is large, the estimation of the asymptotics of their averages from the sampled traffic is easy in practice. Theoretical results on these variables are derived in the next section.

4. MATHEMATICAL PROPERTIES OF THE OBSERVABLES

4.1. Definitions and Le Cam's inequality. For $j \geq 0$, the variable W_j defined by Equation (2) is a sum of Bernoulli random variables, namely

$$W_j = \mathbb{1}_{\{\hat{v}_1=j\}} + \mathbb{1}_{\{\hat{v}_2=j\}} + \dots + \mathbb{1}_{\{\hat{v}_K=j\}},$$

where \hat{v}_i is the number of times that the i th flow has been sampled. If these indicator functions were independent, by assuming that K is large, one could use to estimate the distribution of W_j either via a Poisson approximation (in a rare event setting) or via a central limit theorem (in a law of large numbers context). Since the total number of samples is known, the sum of the random variables \hat{v}_i for $i = 1, \dots, K$ is known and then, the Bernoulli variables defining W_j are *not* independent.

To overcome this problem, we make use of general results on the sum of Bernoulli random variables. Let us consider a sequence (I_i) of Bernoulli random variables,

i.e. $I_i \in \{0, 1\}$. The distance in total variation between the distribution of $X = I_1 + \dots + I_i + \dots$ and a Poisson distribution with parameter $\delta > 0$ is defined by

$$\begin{aligned} \|\mathbb{P}(X \in \cdot) - \mathbb{P}(Q_\delta \in \cdot)\|_{tv} &\stackrel{\text{def.}}{=} \sup_{A \subset \mathbb{N}} |\mathbb{P}(X \in A) - \mathbb{P}(Q_\delta \in A)| \\ &= \frac{1}{2} \sum_{n \geq 0} \left| \mathbb{P}(X = n) - \frac{\delta^n}{n!} e^{-\delta} \right|. \end{aligned}$$

The Poisson distribution Q_δ with mean δ is such that

$$\mathbb{P}(Q_\delta = n) = \frac{\delta^n}{n!} \exp(-\delta).$$

Note that the total variation distance is a strong distance since it is uniform with respect to all events, i.e., for all subset s A of \mathbb{N} ,

$$|\mathbb{P}(X \in A) - \mathbb{P}(Q_\delta \in A)| \leq \|\mathbb{P}(X \in \cdot) - \mathbb{P}(Q_\delta \in \cdot)\|_{tv}.$$

The following result (see Barbour *et al.* [5]) gives a tight bound on the total variation distance between the distribution of X and the Poisson distribution with the same expected value when the Bernoulli variables are independent. In spite of the fact that this result is not directly applicable in our case, we shall show in the following how to use it to obtain information on the distributions of the observables W_j .

Theorem 1 (Le Cam's Inequality). *If the random variables (I_i) are independent and if $X = \sum_i I_i$, then*

$$(3) \quad \|\mathbb{P}(X \in \cdot) - \mathbb{P}(Q_{\mathbb{E}(X)} \in \cdot)\|_{tv} \leq \sum_i \mathbb{P}(I_i = 1)^2 = \mathbb{E}(X) - \text{Var}(X)$$

If X is a Poisson distribution then $\text{Var}(X) = \mathbb{E}(X)$, the above relation shows that to prove the convergence to a Poisson distribution one has only to prove that the expectation of the random variable is arbitrarily close to its variance.

4.2. Estimation of the mean value of the observables. We consider the 1-out-of- κ_s deterministic sampling technique, where one packet is selected every other κ_s packets. In addition, we suppose that traffic on the observed link is sufficiently mixed so that the mixing condition given by Definition 1 holds and that there are no dominating flows in traffic so that the negligibility condition (Definition 2) also pertains.

It is assumed that during a time interval of length Δ , there are K flows composed of at least B_{min} packets, where B_{min} is defined in Section 2. It has been seen that the number of packets in these flows follows a Pareto distribution defined by Relation (1) for some exponent a and parameters B_{min} and B_{max} . Let S be a random variable whose distribution is given by Relation (1) for all $x \geq B_{min}$. From our experiments, S is the size of a "typical" flow whose size is in the interval $[B_{min}, B_{max}]$. See the discussion at the end of Section 2 for the flows of size greater than B_{max} . Of course the sizes of mice are not represented by this random variable. The variable V denotes the total number of packets in the observation window, note that it includes not only the elephants but also the mice.

Note that V is the sum of the number of packets in elephants and mice. If v_i is the number of packet in the i th elephant, then v_i has the same Pareto distribution

as S (i.e., $v_i \stackrel{\text{dist.}}{=} S$) and $V \geq v_1 + v_2 + \dots + v_K$. The difference $V - v_1 - v_2 - \dots - v_K$ is the number of packets of mice.

Proposition 1 (Mean Value of the Observables). *If K elephants are active in a time window of length Δ , the mean number $\mathbb{E}(W_j)$ of flows sampled j times, $j \geq 1$, satisfies the relation*

$$(4) \quad \left| \frac{\mathbb{E}(W_j)}{K} - \mathbb{Q}_j \right| \leq p_s \mathbb{E} \left(\frac{S^2}{V} \right),$$

where \mathbb{Q} is the probability distribution defined by

$$\mathbb{P}(\mathbb{Q} = j) \stackrel{\text{def}}{=} \mathbb{Q}_j = \mathbb{E} \left(\frac{(p_s S)^j}{j!} e^{-p_s S} \right),$$

and $p_s = 1/\kappa_s$ is the sampling rate.

From Equation (4) one gets that the larger the total volume V of packets is, the better is the approximation of $\mathbb{E}(W_j)/K$ by \mathbb{Q}_j .

Proof. The number of times \hat{v}_i that the i th flow is sampled in the time interval is given by

$$\hat{v}_i = B_1^i + B_2^i + \dots + B_{p_s V}^i,$$

where, due to the mixing condition, B_ℓ^i is equal to one if the ℓ th sampled packet is from the i th flow, which event occurs with probability v_i/V . Note that the total number of sampled packets is $p_s V$.

Conditionally on the values of the set $\mathcal{F} = \{v_1, \dots, v_K\}$, the variables $(B_\ell^i, \ell \geq 1)$ are independent Bernoulli variables. For $1 \leq i \leq K$, Le Cam's Inequality (3) gives therefore the relation

$$\|\mathbb{P}(\hat{v}_i \in \cdot \mid \mathcal{F}) - Q_{p_s v_i}\|_{tv} \leq p_s \frac{v_i^2}{V}.$$

By integrating with respect to the variables v_1, \dots, v_K , this gives the relation

$$\|\mathbb{P}(\hat{v}_i \in \cdot) - \mathbb{Q}\|_{tv} \leq p_s \mathbb{E} \left(\frac{v_i^2}{V} \right).$$

In particular, for $j \in \mathbb{N}$, $|\mathbb{P}(\hat{v}_i = j) - \mathbb{Q}_j| \leq p_s \mathbb{E} (S^2/V)$. Since

$$\mathbb{E}(W_j) = \sum_{i=1}^K \mathbb{P}(\hat{v}_i = j),$$

by summing on $i = 1, \dots, K$, one gets

$$|\mathbb{E}(W_j) - K\mathbb{Q}_j| \leq p_s K \mathbb{E} \left(\frac{S^2}{V} \right)$$

and the result follows. \square

If the number of packets per flow were constant, then \mathbb{Q} would be a Poisson distribution with parameter $p_s S$, the variable S being in this case a constant. The above inequality shows that at the first order the expected value of W_j is $p_s \mathbb{E}(S)$. The expression of \mathbb{Q} , however, indicates that higher order moments of S play a significant role. For example, if the variable S has a significant variance, then the classical rough reduction, which consists of assuming that the size of a sampled elephant is $p_s S$, is no longer valid for estimating the original size of the elephant.

Under the negligibility condition, we deduce that

$$\left| \frac{\mathbb{E}(W_j)}{K} - \mathbb{Q}_j \right| \leq p_s \varepsilon,$$

where ε appears in Definition 2 and is assumed to be much less than 1. This implies that Inequality (4) is tight and the quantity $\mathbb{E}(W_j)/K$ can accurately be approximated by the quantity \mathbb{Q}_j , when no flows are dominating in traffic.

We are now ready to state the main result needed for estimating the number K of elephants from sampled data.

Proposition 2 (Asymptotic Mean Values). *Under the same assumptions as those of Proposition 1,*

$$(5) \quad \lim_{K \rightarrow +\infty} \frac{\mathbb{E}(W_{j+1})}{\mathbb{E}(W_j)} \sim 1 - \frac{a+1}{j+1}$$

and

$$(6) \quad \lim_{K \rightarrow +\infty} \frac{\mathbb{E}(W_j)}{K} \sim a(p_s B_{min})^a \frac{\Gamma(j-a)}{j!},$$

if $B_{max} \gg 1$ and $p_s B_{min} \ll 1$, where Γ is the classical Gamma function defined by

$$\Gamma(x) = \int_0^{+\infty} u^{x-1} e^{-u} du, \quad x > 0.$$

Proof. For $j \geq 1$,

$$\mathbb{Q}_j = \mathbb{E} \left(\frac{(p_s S)^j}{j!} e^{-p_s S} \right) \sim a B_{min}^a \frac{p_s^{a+1}}{j!} \int_{B_{min}}^{+\infty} (p_s u)^{j-a-1} e^{-p_s u} du$$

and then

$$\mathbb{Q}_j \sim a B_{min}^a \frac{p_s^a}{j!} \int_{p_s B_{min}}^{+\infty} u^{j-a-1} e^{-u} du \sim a(p_s B_{min})^a \frac{\Gamma(j-a)}{j!},$$

since $p_s B_{min} \sim 0$. Therefore, by using the relation $\Gamma(x+1) = x\Gamma(x)$ we obtain the equivalence

$$\frac{\mathbb{Q}_{j+1}}{\mathbb{Q}_j} \sim \frac{j-a}{j+1}.$$

The proposition follows by using the fact that the upper bound of Equation (4) of Proposition 1 goes to 0 by the law of large numbers. \square

As it will be seen later in the next section, Relation (5) is used to estimate the exponent a of the Pareto distribution of the number of packets of elephants, the quantities $\mathbb{E}(W_j)$ and $\mathbb{E}(W_{j+1})$ being easily derived from sampled traffic. The quantity K will be estimated from Relation (6). The estimation of the parameter B_{min} from sampled traffic as well as the correct choice of the integer j will be discussed in the next section.

5. APPLICATIONS

5.1. Traffic parameter inference algorithm. In this section, it is assumed that only sampled traffic is available. The methods described in Section 2 to infer the statistical properties of the flows cannot be applied and another algorithm has to be defined. For the experiments carried out in the present section, the sampling factor $p_s = 1/\kappa_s$ has been taken equal to 1/100. To infer flow characteristics, we have to give the proper definition of the mouse and elephant dichotomy (the parameter B_{min}) and to estimate the coefficient of the corresponding Pareto distribution (the parameter a in Relation (1)).

Relation (5) gives the following equivalence, for $j \geq 1$ sufficiently large so that the impact of mice on $\mathbb{E}(W_j)$ is negligible,

$$(7) \quad a \sim a(j) \stackrel{\text{def.}}{=} (j+1) \left(1 - \frac{\mathbb{E}(W_{j+1})}{\mathbb{E}(W_j)} \right) - 1,$$

and Relation (6) yields an estimate of the number of elephants, i.e. the number of flows with a number of packets greater than or equal to B_{min} ; we specifically have

$$(8) \quad K \sim K(j) \stackrel{\text{def.}}{=} \frac{j! \mathbb{E}(W_j)}{a(j)(p_s B_{min})^{a(j)} \Gamma(j - a(j))}.$$

These estimations greatly depend on some of the key parameters used to obtain a convenient and confident Pareto representation of the size of the flows, in particular the size of the time window Δ and the lower bound B_{min} for the elephants. The variable Δ is chosen so that

- (1) the number of flows sampled twice is sufficiently large in order to obtain a significant number of samples so that the estimation of the mean values of the random variables W_j for $j \geq 2$ is accurate; this requires that Δ should not be too small,
- (2) Δ is not too large in order to preserve the unimodal Pareto representation (see Section 2 for a discussion).

To count the average number of flows sampled j times, the parameter j should be chosen as large as possible in order to neglect the impact of mice (for which the Pareto representation does not hold) but not too large so that the statistics are robust to compute the mean value $\mathbb{E}(W_j)$.

In the experimental work reported below, special attention has been paid to the choice of the *universal* constants, i.e., those constants used in the analysis of sampled data, that do not depend on the traffic trace considered. In our opinion, this is a crucial in an accurate inference of traffic parameters from sampled data. These constants are defined in the algorithm given in Table 5.

TABLE 5. Algorithm used to identify Δ and the Pareto parameter from sampled traffic.

-
- Choose Δ so that $80 \leq \mathbb{E}[W_2] \leq 100$;
 - Choose j so that $|a(j) - a(j+1)|$ computed with Equation (7) is minimized with for all j such that $\mathbb{E}[W_j] \geq 5$.
 - B_{min} is the smallest integer so that the probability that a flow of size greater than B_{min} is sampled more than j times is greater than $p_s/10$;
-

5.2. Experimental results. Concerning the estimation of the constants B_{min} , the numerical results obtained by using the algorithm given in Table 5 are presented in Table 6, where the values of the different B_{min} estimated by the algorithm are compared against the values given in Section 2. As it can be observed, the proposed algorithm yields a rather conservative definition of elephants (i.e., flows of size greater than or equal to B_{min}).

TABLE 6. Elephants for the France Telecom ADSL and the Abilene traffic traces.

	ADSL A	ADSL B Up	ADSL B Down	Abilene A	Abilene B
B_{min}	20	29	39	89	79
estimated B_{min}	21	45	45	77	77

The main results are gathered in Table 7 giving the quantities K and a estimated by using Equations (7) and (8) for different values of the parameters j . These values are compared against the experimental values a_{exp} and K_{exp} , referred to as the “real” a and K obtained from the complete traffic traces in Section 2. The accuracy of the estimation of K is generally quite good except for the Abilene A trace where the error is significant although not out of bound. A look at the corresponding figure in Section 2 gives a plausible explanation for this discrepancy: For this trace, the Pareto representation is not very precise.

Finally, it is worth noting from Table 7 that the estimation of the important parameter a describing the statistics of flows is also quite accurate. The error in this table is defined as

$$\frac{K(j) - K_{exp}}{K_{exp}}.$$

TABLE 7. Estimations of the Number of Elephants from Sampled traffic

Trace	Δ	j	$\mathbb{E}(W_j)$	$\mathbb{E}(W_{j+1})$	a_{exp}	$a(j)$	K_{exp}	$K(j)$	Error
ADSL A	5s	3	12.89	3.33	1.85	1.95	943.71	1031.04	9.25%
ADSL B Do	15s	4	9.7	4.75	1.49	1.55	414.90	404.13	2.59%
ADSL B Up	15s	4	7.46	2.97	1.97	2.00	453.01	462.68	2.13%
ABILENE A	1s	5	6.04	3.21	1.38	1.81	217.44	270.79	24.53%
ABILENE B	1s	5	6.1	3.7	1.36	1.51	209.12	197.12	5.74%

Remark. As pointed out by Loiseau *et al.* [19], the determination of Δ is crucial. Recall it is determined explicitly by the first step of our algorithm, see Table 5.

6. CONCLUSION

We have developed in this paper one method of characterizing flows in IP traffic by a few parameters and another one of inferring these parameters from sampled data obtained via deterministic 1-out-of- k sampling. For this purpose, we have made some restrictive assumptions, which are in our opinion essential in order to establish an accurate characterization of flows. The basic principle we have adopted consists of describing flows in successive observation windows of limited length, which has to satisfy two contradicting requirements. On the one hand,

observation windows shall not be too large in order to preserve a description of flow statistics as simple as possible, for instance their size by means of a simple Pareto distribution.

On the other hand, a sufficiently large number of packets has to be present in each observation window in order to be able of computing flow characteristics with sufficient accuracy, in particular the tail of the distribution of the flow size. By assuming that large flows (elephants) have a size which is Pareto distributed, we have developed an algorithm to determine the optimal observation window length together with the parameters of the Pareto distribution. The location parameter B_{min} (see Equation (1)) leads to a natural division of the total flow population into two sets: those flows with at least B_{min} packets, referred to as elephants, and those flows with less than B_{min} packets, called mice. This method of characterizing flows has been tested against traffic traces from the France Telecom and Abilene networks carrying completely different types of traffic.

For interpreting sampled data, we have made assumptions on the sampling process. We have specifically supposed that flows are sufficiently interleaved in order to introduce some randomness in the packet selection process (mixing condition) and that there are no dominating flows so that there is no bias with regard to the probability of sampling a flow (negligibility condition). These two assumptions allows us to establish rigorous results for the number of times an elephant is sampled, in particular for the mean values of the random variables W_j , $j \geq 1$.

Of course, when analyzing sampled data, the original flow statistics are not known. In particular, the length of the observation window necessary to characterize the flow size by means of a unique Pareto distribution is unknown. To overcome this problem, we have proposed an algorithm to fix the observation window length and the minimal length of elephants. Then, by choosing the index j sufficiently large so as to neglect the impact of mice, the theoretical results are used to complete the flow parameter inference. This method has been tested against the Abilene and the France Telecom traffic traces and yields satisfactory results.

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